

Steering compensation for strong vertical refraction gradients in a long-distance free-space optical communication link over water

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ABSTRACT

It is important to be able to characterize and compensate for refraction effects in free-space optical laser communication (FSO lasercom). The refractive index depends on various properties of the propagation medium such as temperature, pressure, and moisture, with temperature having the largest affect. Very strong but slow-varying thermal gradients have been observed at the NRL Chesapeake Bay lasercom testbed, which offers a 16 km one-way (32 km round-trip) FSO lasercom link over water. Thermal gradients affect the elevation-pointing angle, and their magnitudes are a function of the time of day and year and also the weather conditions. These vertical refraction errors are corrected by the use of a fiber positioner controlled by a position-sensing detector (PSD). This system is implemented into the receiver at the NRL Chesapeake Bay lasercom testbed. System test results will be presented.

Keywords: Free-space optical lasercom, thermal gradients, refractive index, fiber positioner

1. INTRODUCTION

In order to maintain a quality free-space laser communications link, over an extended period of time, certain atmospheric effects must be compensated for. Temperature variations throughout the day greatly affect the atmosphere's refractive index. These refraction effects can cause large vertical fluctuations in the pointing angle¹. A fiber positioner directed by a position-sensing detector (PSD) is able to correct the elevation errors caused by the strong thermal gradients. The system was installed and tested at the Naval Research Laboratory Chesapeake Bay lasercom testbed^{2,3,4} located at NRL's Chesapeake Bay Detachment (CBD).

2. TURBULENCE MEASUREMENTS

Figure 1 shows the compilation of approximately 3 months of turbulence data taken over the Bay at the Lasercom Testbed⁵. C_n^2 values observed cover only a small range (one order of magnitude) compared to those typically measured over land (roughly four orders of magnitude or more). Also it is important to note that turbulence mitigation appears to be easier in the maritime environment because the C_n^2 values recorded rarely rise above 10^{-14} .

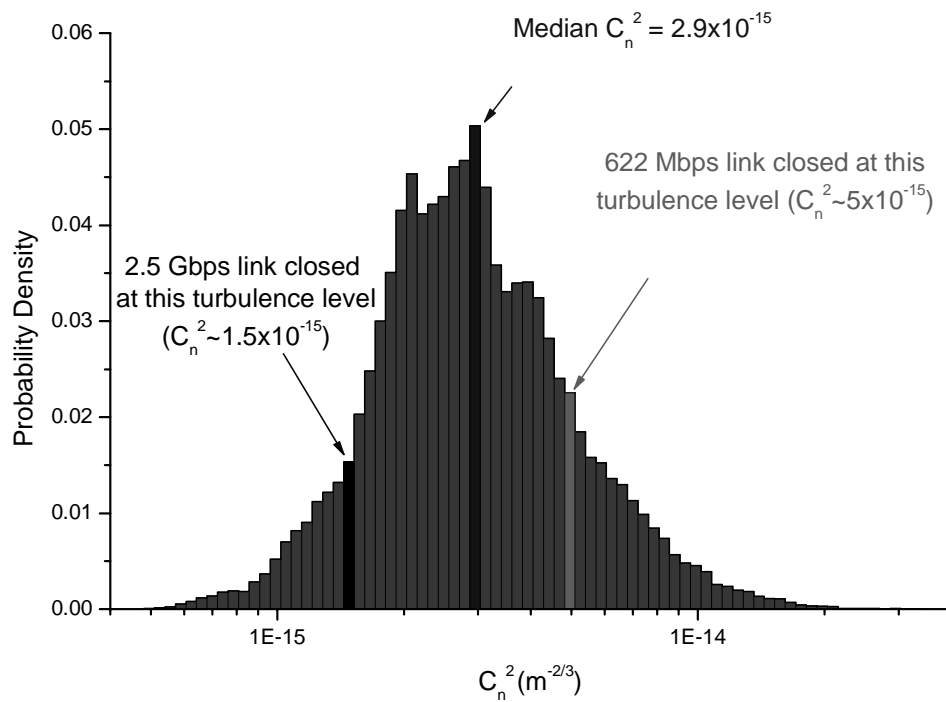


Figure 1. PDF of C_n^2 data taken over the Chesapeake Bay from April - July 2003 (from passive turbulence monitor⁵; estimated from angle of arrival variance)

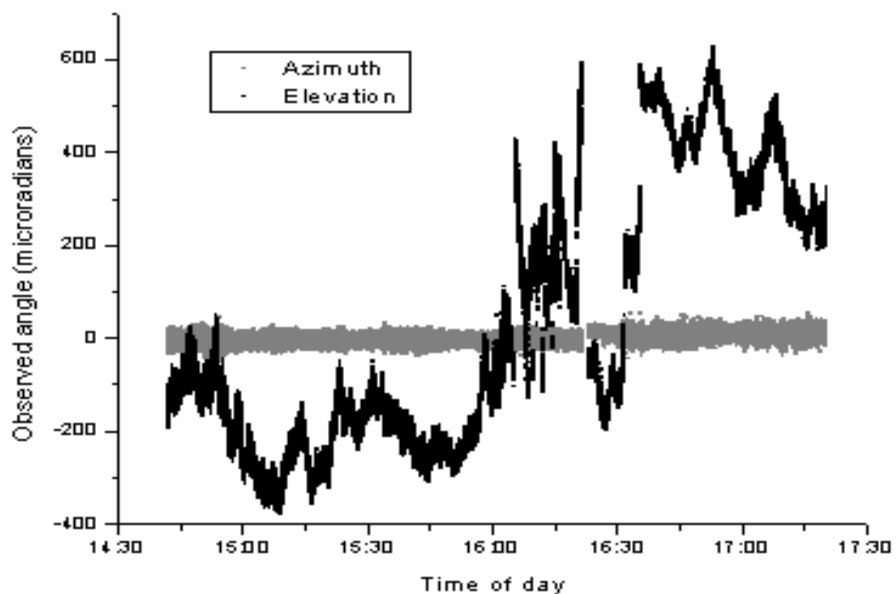


Figure 2: Apparent change in azimuth and elevation of received laser at NRL-CBD after reflection from retro-reflectors on Tilghman Island tower on February 8th, 2005.

Figure 2 shows the very large changes in elevation angle-of-arrival into the receiver observed while azimuthal angle-of-arrival showed no significant change. Rapid changes in elevation angle were clear at approximately 16:05 and 16:40 which likely corresponded to sharp boundaries of thermal layers passing through the path to the retro-reflectors resulting in rapid jumps of the apparent retro-reflector elevation. The total angular deviation observed over this three hour period was very large (~ 1.5 mrad). The variance in elevation was $70627 \mu\text{rad}^2$ and in azimuth was $92.1 \mu\text{rad}^2$ over this period. The rapid changes typically occurred over 10's of seconds making the problem of following the beam through these transits a low frequency (<1 Hz) tracking problem and not a high frequency (>1 Hz) turbulence mitigation or adaptive optics problem.

3. EXPERIMENTAL SETUP

The transmitter and receiver are co-located at NRL-CBD on a cliff approximately 30 meters above sea level. An array of corner-cube retro-reflectors is mounted 16.2 km away on a tower on NRL's Tilghman Island facility. The transmitter consists of a 1556 nm CW seed laser amplified by a 5 Watt erbium doped fiber amplifier (EDFA) which is then fiber-coupled to a 4" collimating lens on a Sagebrush gimbal mount. For this experiment, the EDFA was run at only 31.2 dBm, or 1.3 Watts. The receiver is a 16" Meade telescope with a focal length of four meters. A round-trip FSO lasercom link over the Chesapeake Bay is used to test the fiber positioner. The fiber positioner is installed at the focus of the 4" lens of the transmitter, shown in Figure 3.

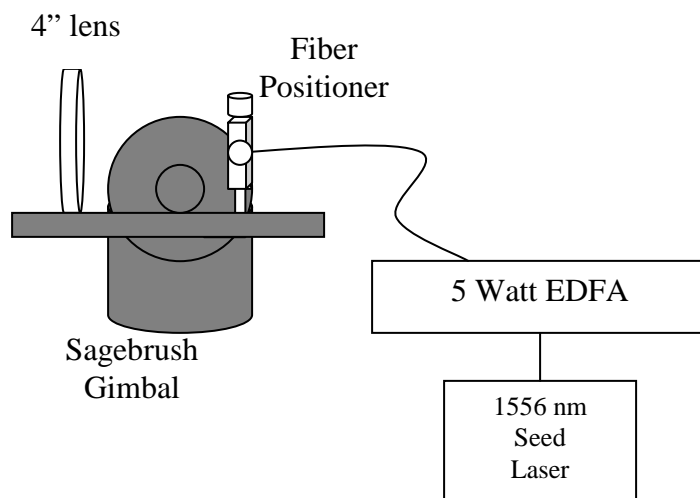


Figure 3: Transmitter Block Diagram with fiber positioner at the focus of the 4" collimating lens to correct the pointing of the transmitted beam.

Light received into the Meade is then directed onto the PSD, which is at the focus of the 16" receiving telescope. Figure 4 below illustrates the receiver system.

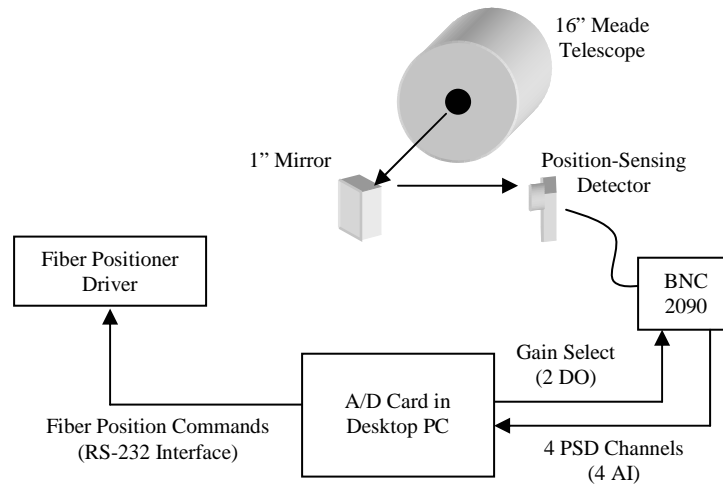


Figure 4: Receiver Block Diagram for characterization of fiber positioner. The PSD is at the focus and the return light is directed onto it with a 1" mirror at a 45 degree angle from the 16" Meade telescope.

Data was taken with and without active correction by the fiber positioner.

3.1 Fiber Positioner

The fiber positioner that is used is a commercially available New Focus Model 8051 with Picomotor drivers and actuators. Its minimum incremental motion is less than 30 nm, and its maximum speed is 1 mm per minute. A desktop PC communicates with the drivers through an RJ-45 connection using an RS-232 serial interface. The actuators use the basic laws of dynamic and static friction.

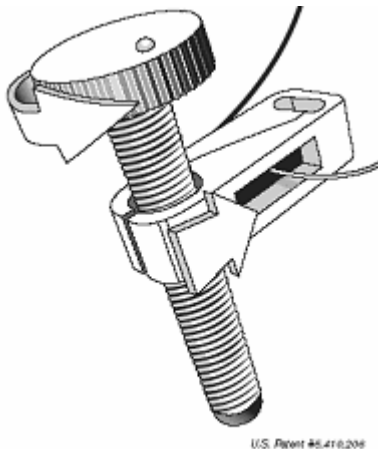


Figure 5: Drawing of Picomotor actuator⁶

Threaded jaws are placed around a precision screw and the sides of the jaw connected to opposite ends of a piezoelectric transducer. A slow electrical signal is applied to the piezo causing the jaws to slowly slide in opposite directions, turning the screw with high static friction. Then, a fast signal is sent to quickly return the jaws to their starting position while keeping the screw motionless due to its inertia and low dynamic

friction. To turn the screw in the opposite direction, the order of the fast and slow signals is simply reversed. Because it is a “stick-slip” actuator, the actual angle change differs with the direction of rotation. The calibration is described in a later section.

3.2 Position-Sensing Detector

For this work, a PSD from Judson Technologies is used⁷. It is a Germanium device with an active area of 5 mm square. Its response at 1550nm is .9-.95 A/W. Table 1 below shows the details of the gain settings for the four PSD channels.

Table 1: Select lines, sensitivity, and bandwidth of the gain settings of the PSD.

A0	A1	Gain (KV/A)	Bandwidth (KHz)
Gnd	Gnd	6.03	79.3
Gnd	+5V	19.135	78.25
+5V	Gnd	60.850	77.45
+5V	+5V	150.384	74.675

On each of the four output channels, x1, x2, y1, and y2, is a matched trans-impedance amplifier.

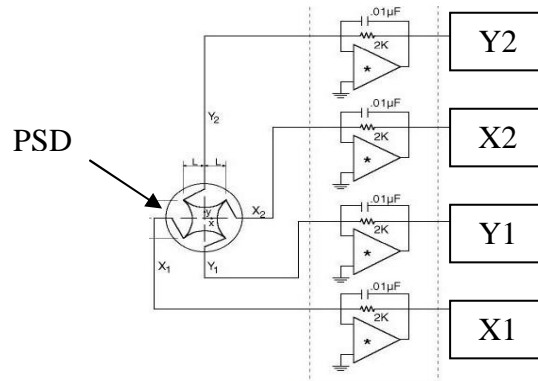


Figure 6: Drawing of the physical positions of the four separate channels on the PSD

Using these four channels, normalized outputs for x and y positions are calculated with the following equations:

$$x/L = [(x2 + y2) - (x1 + y1)] / (x1 + x2 + y1 + y2) \quad (1)$$

$$y/L = [(x2 - y2) - (x1 - y1)] / (x1 + x2 + y1 + y2) \quad (2)$$

3.3 Control Hardware and Software

A BNC 2090 takes the four analog channels from the PSD and feeds them into an analog to digital converter in a desktop PC. Two digital outputs are also used on the BNC 2090 to select the gain setting of the PSD. The PSD is run at the lowest gain setting throughout all of the tests. LabVIEW is utilized to calculate the position of the beam on the PSD and then convert that into the appropriate position commands

to send to the fiber positioner. The four channels out of the PSD, read at a rate of 20 kHz, are averaged over two seconds to reduce noise.

Each of the four channels is checked for validity in several ways. At least 1000 of the 40000 points have to give a valid position in order to be considered. The intensity of the light on the PSD must be above a set minimum value of 100 mV to ensure there is a reliable return signal and is not dominated by noise. The command position is calculated as a running average to include its position history, and 100 steps is the maximum acceptable change in steps from the previous position. Adjustable weighting factors are used for the new calculated position and the previous positions. Equation 3 below describes the weighted running average.

$$Y_i = \alpha Y_{\text{new}} + \beta Y_{i-1}, \quad (3)$$

Where Y_i is the new command position, Y_{i-1} is the last commanded position and Y_{new} is the new position calculated from the averaged four channels. α and β are the weighting factors for the new position and the previous command position. The sum of the weighting factors must equal 1. Also, before the fiber positioner starts its active tracking of the spot, it must have 10 valid positions. All of these checks are to make sure the fiber positioner remains stable.

The Sagebrush gimbal was used as a reference to determine the conversion from the number of steps on the fiber positioner to the actual spot movement in the focal plane. One step in the positive vertical direction corresponds to 0.1545 micro radians and a step in the negative vertical direction yields 0.129 micro radians. With the Meade having a 4 meter focal length, 1mm of motion on the PSD is approximately equal to 1618 or 1938 steps on the fiber positioner in the positive or negative direction, respectively. These were the gains entered into the LabVIEW GUI.

4. DATA AND RESULTS

Various data sets were taken on July 8th, 2005. As the sun set, the temperature dropped, and a steady change in the elevation pointing angle was observed. There was not any active tracking with the fiber positioner at the start of the data set shown in Figure 7. Within fifteen minutes, the intensity on the position-sensing detector began to drastically decrease. Once the tracking was enabled at approximately 21:35, the intensity was immediately recovered.

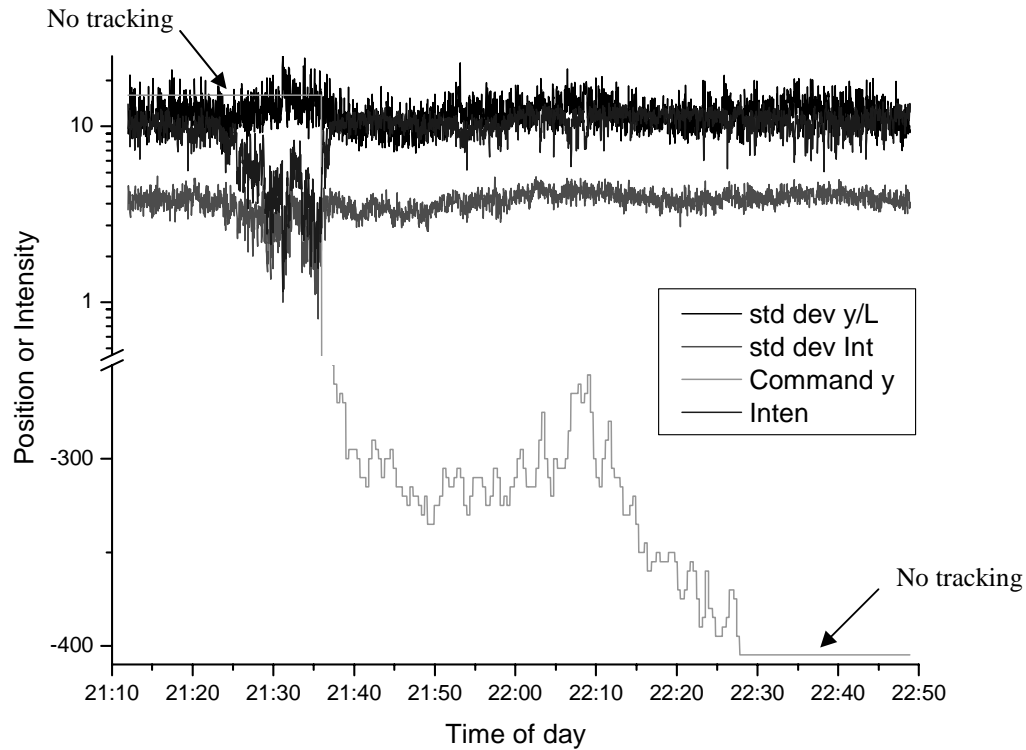


Figure 7: The standard deviation of y/L and intensity along with the command y and absolute intensity on July 8th, 2005 during sunset with low turbulence conditions.

The fiber positioner tracked the beam for just under an hour. The control software was set so that the fiber positioner did not move until there was a minimum of a 5 step change in the command position. Due to the minimum step size being so small, there were many movements. Figure 8 below shows the command y position from an earlier data set of constant tracking.

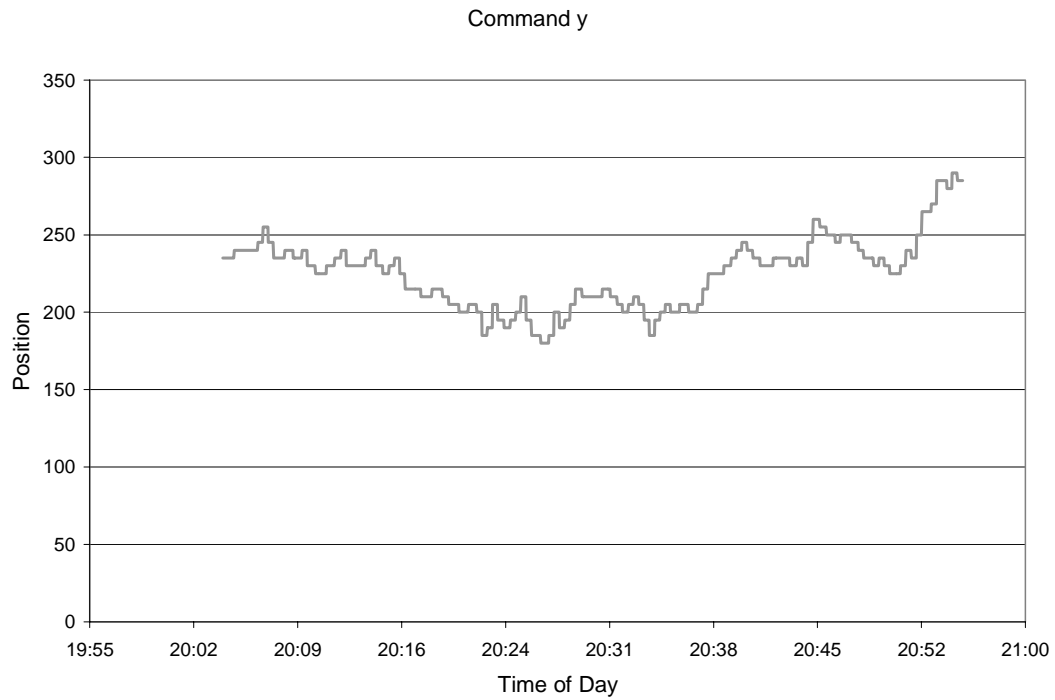


Figure 8: Command position in the y direction over a period of ~50 minutes of active tracking with the fiber positioner.

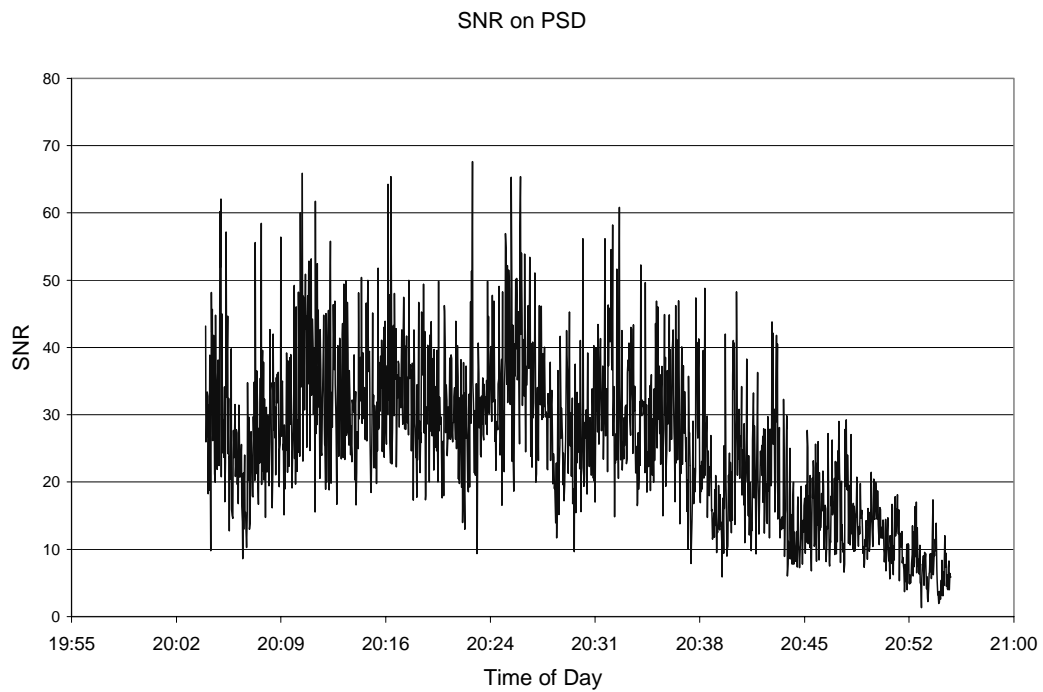


Figure 9: Signal-to-Noise Ratio on the Position-Sensing Detector with tracking enabled on the fiber positioner during the entire data set.

For this data, the fiber positioner was commanded to move 99 times with a minimum change of 5 steps. Conversely, only 5 movements would have been needed if the step size was increased to 30 steps, yielding an average of almost 20 times fewer movements. With each movement of the fiber positioner, the error in actual position increased. Over long periods of time it can become noticeable, which was the case for this data set. At the very end of the time period, the SNR began to drop, as shown in Figure 9. By increasing the minimum required step size, the number of position changes commanded would decrease. This should increase the amount of time before the error in actual position of the fiber affects the link quality.

5. CONCLUSIONS

The use of a fiber positioner and PSD improved the stability of the FSO lasercom system across the Chesapeake Bay in the presence of strong thermal gradients. They are seen most prominently at sunrise and sunset and can cause large gradual shifts in the elevation pointing-angle. There are still enhancements to be made on the fiber positioner and PSD tracking system. For instance, the control software is currently using open-loop control. However, with the proper adjustments to lengthen the time in between command position updates, the fiber positioner can be a very effective tool. The minimum step size can be increased as well as the time average of the four PSD output channels. Maintaining the link quality can now be automated for extended periods of time.

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